2004-10001BW
10 pages

Injury Based Glass Hazard Assessment

By Sarah Meyer, Lyn Little, and Ed Conrath

1 Introduction

In a blast scenario, glass fragmentation is a major cause of injuries. Physical security assessments typically have defined the predicted hazard due to window failure by using the British Glazing Hazard Guide criteria, which is based upon the post-test observations of the distribution of fragments generated during an airblast test, and not the injuries that those fragments would cause. When compared to a recently developed glass penetration injury model, the British Glazing Hazard Guide criteria have been shown to be extremely conservative. By applying this glass penetration injury model, the hazard can be based on the severity of the predicted injuries due to individual shard impacts.

The US Army Technical Center for Explosive Safety (USATCES), in conjunction with the US Army Corps of Engineers Protective Design Center, contracted with Applied Research Associates (ARA) to develop injury based glass hazard assessment tools using the Shard Fly-Out Model (SFOM) and Multi-Hit Glass Penetration (MHGP) Model. The SFOM determines window breakage and generates and propagates a statistically realistic set of shards; the MHGP predicts the severity of the injury caused by individual shard impacts. Both models were developed by Applied Research Associates, Inc. (ARA) under funding from the Defense Threat Reduction Agency (DTRA) and Technical Support Working Group (TSWG). Subsequently, ARA was tasked with using these models to develop a set of glass penetration range-to-effect curves for implementation into software suitable for a Personal Digital Assistant (PDA). These range-to-effect curves were generated for monolithic annealed, monolithic fully tempered, and annealed insulating glass unit windows in a variety of dimensions and lite thicknesses. The PDA tool will be employed in site inspections to evaluate the likelihood of injury due to glass breakage. Additionally, ARA has adapted the SFOM and MHGP for use in HazL, a single degree of freedom prediction code for predicting glass response to airblast loading.

This paper provides a brief overview of the SFOM and MHGP models, followed by discussions of the PDA and HazL applications of these models.

2 The Shard Fly-Out Model and Multi-Hit Glass Penetration Model

The Shard Fly-Out Model (SFOM) predicts the size, shape and velocity distributions of the shard fields from shock-loaded windows. The model is semi-empirical, based mostly on the data from sixty-nine tests of shock-tube loaded windows. Some analytical modeling is also employed to define the limits of the distributions and different response thresholds.

In the shard fly-out test program conducted by ARA at the BakerRisk shock tube, four glass types were evaluated: Annealed, Fully Tempered, IGU, and Laminated. The first three types comprised the majority of the tests. Two window sizes were tested: 2ft by 4ft and 4ft by 5ft. Various thicknesses and load levels were evaluated. The footage from high-speed digital cameras was used to determine the size, shape, and velocities of the shard clouds. The size and shape of each shard was determined with a commercial image processing software package (Figure 1).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**

4. TITLE AND SUBTITLE **Injury Based Glass Hazard Assessment**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Applied Research Associates,San Antonio,TX,78213**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002168. Presented at the DoD Explosives Safety Seminar (31st) Held in San Antonio, Texas on August 24-26, 2004.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

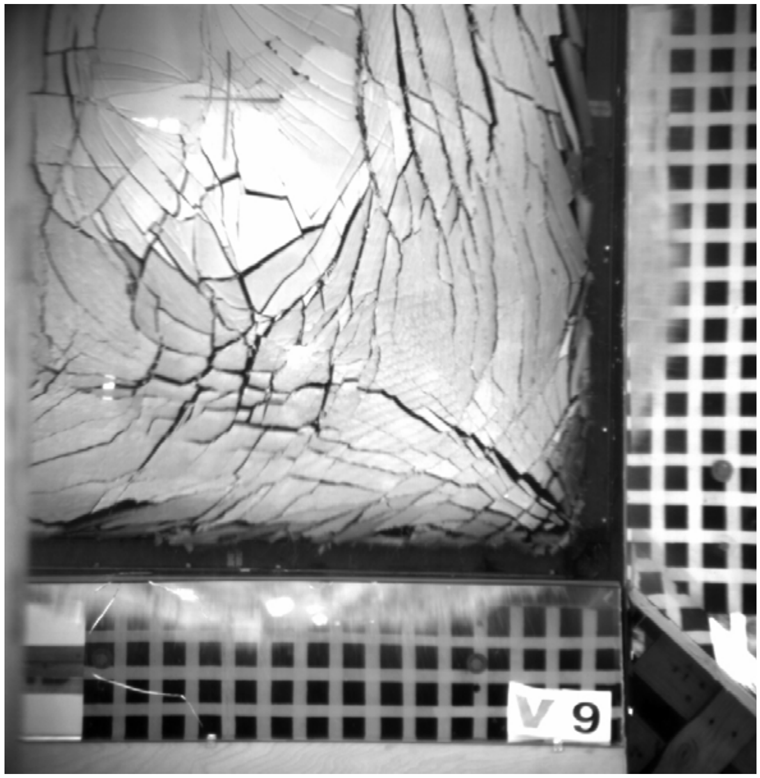

Figure 1. Shards Produced as a Monolithic Annealed Window Fails in the Shard Fly-Out Test Program

To develop the Multi-Hit Glass Penetration Model (MHGP), two glass injury test programs were completed: the “single-shot” tests and the “multi-hit” tests. The single-shot tests were conducted by ARA with test support from the University of Virginia’s Center for Applied Biomechanics. In this test series, glass fragments of three sizes and shapes were launched at three velocities into ballistic gelatin, cadaveric arm and cadaveric neck specimens. The results of these tests were used to evaluate the low-velocity biofidelity of ballistic gelatin and to make improvements to a cutting model previously implemented in the glass penetration module of the Joint Technical Coordinating Group’s Operational Requirements-based Casualty Assessments code (ORCA-Glass). The multi-hit tests were conducted by ARA with test support from the US Army’s Institute for Surgical Research. In these tests, four ballistic gelatin targets were placed three meters behind three annealed windows and one fully tempered glass window (Figure 2). Using BakerRisk’s shock tube, the windows were broken at nominal load levels (Figure 3). All impacts causing lacerations were recorded, and if the glass imbedded in the gelatin, it was removed and the fragment weight was also recorded. From the detailed human cross sections available for the Visible Man, potential organ injuries were extrapolated and injury severities were inferred.

Figure 2. Blast Tube Outlet and Gelatin Target for the Multi-Hit Tests

Figure 3. Annealed Shards Embedded in Ballistic Gelatin from a Multi-Hit Test

The MHGP code was developed to estimate the overall injury severity from multiple glass penetration wounds. Given a blast scenario (window description, blast parameters and the location of a person relative to the window), the MHGP code estimates the severity of injuries caused by glass shards penetrating the person. Using the SFOM, a statistically realistic fragment debris field is generated and propagated outward from the window. For those fragments that impact the person, the ORCA-Glass code simulates the glass penetration through tissue. From each penetration, the user obtains detailed information about the resulting wound, including an Abbreviated Injury Scale (AIS) Score. This data is then passed into the Multi-Hit Injury Severity model which accumulates the injury severities from each shard penetration to compute an overall Injury Severity Score (ISS).

3 British Glazing Hazard Guide Criteria

The blast-hazard rating of a glazing system was previously defined for most hazard assessments (including HazL) according to the British Glazing Hazard Guide criteria. Using the British Glazing Hazard Guide criteria, glazing hazards are defined as follows (Figure 4):

- No Break: No visible damage to the glazing or frame.
- Minimal Hazard: Glazing fragments inside the test structure are within a maximum distance of 1 meter from the window line.
- Low Hazard: Glazing fragments are thrown into the room for a distance of 1 to 3 meters, but do not exceed a height of 0.5 meters above the floor at the 3 meter distance.
- High Hazard: Glazing fragments are thrown at high velocity into the occupied space and impact the vertical surface at 3m behind the window above a 0.5 meter height.

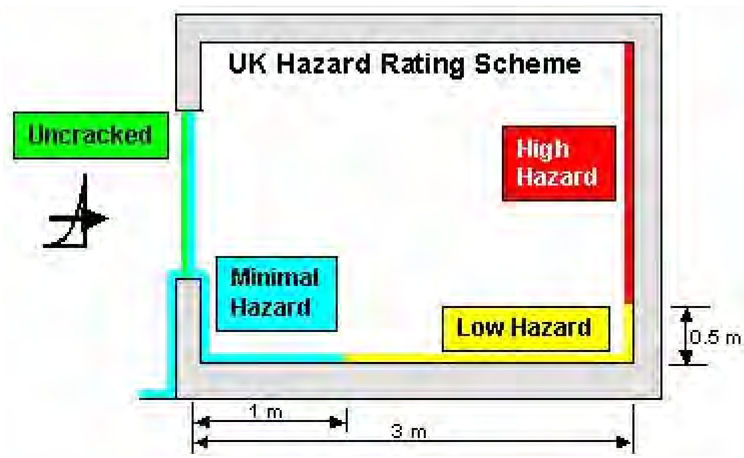

Figure 4. Hazard level criteria used in HazL

The MHGP and multi-hit glass penetration tests were used to evaluate the British Glazing Hazard Guide criteria from an injury perspective. The British Glazing Hazard Guide criteria were found to be overly conservative for most pressure and impulse conditions. Additionally, the criteria fail to account for the significance of fragment mass in determining the hazards associated with a window broken by airblast. By using injury-based criteria for retrofits, unnecessary and costly blast mitigation retrofits to windows and buildings may be avoided, provided that the risk is deemed acceptable. However, for design, the hazard levels used by the British and further defined in ASTM F1642 should be used in selecting glazing.

4 Injury-Based Range-to-Effect Data

4.1 GENERATION

To quickly generate the new injury based range-to-effect curves, the MHGP and ORCA-Glass codes were modified to create an iterative version. This modified code iteratively finds the charge standoff boundaries for each of the injury based hazard levels according to the ISS returned. Since the MHGP is based on statistical distributions, each execution of the code may produce slightly different results. To ensure accurate results, the code was set to run each calculation one hundred times. Once fifty percent of the calculations yielded an ISS within the specified hazard level, a hazard level boundary was assigned. The range-to-effect curves generated with the iterative version were used in the PDA Tool.

Initially, the generation of range-to-effect curves was planned only for the 50% boundaries of the ISS values of 25 and 10. Additional range-to-effect curves were added at the 50% boundaries for ISS values of 5 and 1 because these lower injury hazard levels were thought to be useful and more appropriate for USATCES's purpose. An ISS of 5 is the onset of injuries requiring hospitalization, and an ISS of 1 is the onset of injury requiring medical aid.

The injury level descriptions shown in Table 1 are adapted from qualitative injury levels provided by Chuck Oswald of Baker Engineering and Risk Consultants for use in a injury prediction tool, BICADS. The injury levels are intended to be broad enough to stay within the accuracy level of the BICADS prediction method and detailed enough to provide useful information to possible program users ranging from building managers to doctors and first responders. The example injuries listed in Table 1 are the most prevalent injuries observed within each injury level category among the building occupants injured by the Oklahoma City and Khobar Towers bombings. The correlations between ISS and injury levels in Table 1 were based on the ISS of building occupants injured in the Oklahoma City and Khobar Towers bombings who were judged to be within each injury level. The people injured in these two bombings were assigned ISS by the Oklahoma State Department of Health, Injury Prevention Service based on reported and medically documented injuries.

Table 1. Injury Based Hazard Level Definitions

ISS Range	**Proposed Hazard Level**	**Injury Description**	**Example of Injuries**
ISS $\geq$ 25	High Injury	Fatal/Severe Injury	Multiple very serious injuries Primarily fatalities
10 < ISS < 25	Medium Injury	Serious Life Threatening Injury	Very severe lacerations with significant blood loss Severe open bone fractures Crush injuries Skull fractures
5 < ISS $\leq$ 10	Low Injury	Hospitalization Required, Not Immediately Life Threatening	Bone fractures Large numbers of lacerations Artery or tendon lacerations Concussions
1 < ISS $\leq$ 5	Very Low Injury	Medical Aid Necessary, But No Hospitalization Required	Lacerations to face and body from glass fragments Cuts or abrasions to eye Contusions and abrasions
0 $\leq$ ISS $\leq$ 1	Minimal Injury	No Medical Aid Required	No injury Minor bruises and cuts Small foreign object in eyes Hearing loss

The standoff step size used in the MHGP iterative version is scaled by the charge weight. As the charge weight, and therefore the standoff distance, increases, the step size the software uses while searching for the hazard level boundaries also increases.

The US Army Technical Center for Explosive Safety (USATCES) is tasked with determining safety for areas surrounding storage facilities that contain large amounts of explosives. These explosive weights can be significantly larger than those typically considered by the physical security community; for example, storage weights for some facilities can be as large as 500,000-lbs. Therefore, for each window analyzed, the standoff boundaries for High (ISS ≥ 25), Medium (ISS < 25 and > 10), Low (ISS ≤ 10 and > 5), Very Low (ISS ≤ 5 and > 1) and Minimal Injury Hazard (ISS ≤ 1 and ≥ 0), as well as the minimum standoff for No Break were determined for the following charge weights: 20; 50; 250; 1,000; 10,000; 20,000; 30,000; 100,000; 250,000; and 500,000 pounds of TNT equivalent.

The focus of this effort was on typical residential and light commercial windows. Thus, we analyzed monolithic annealed windows, monolithic fully tempered (FT) windows and insulated glass units (IGUs) composed of monolithic annealed lites. Four lite thicknesses were evaluated for each annealed window dimension; two lite thickness combinations were evaluated for IGUs; and two lite thicknesses were evaluated for each FT window dimension. In total, injury-based range-to-effect curves were developed for forty-eight windows.

For each window, three standoffs were used: 4.92 ft (1.5 m), 9.84 ft (3 m), and 16.40 ft (5 m). Finally two angle offsets from the window were employed: 0^{o} (centered on window) and 15^{o} (offset from window). In all cases, the person was facing the window.

Injury based hazard level boundaries are defined by the ISS. As the iterative MHGP code steps through the standoffs for each charge weight, the resulting ISS distribution is analyzed. The hazard level boundary is defined to be the shortest standoff where 50% of the calculations for that standoff have a specific ISS (25, 10, 5, or 1). Once the High Injury Hazard Level boundary is found, the code continues to step through the standoffs to find the Medium, Low, Very Low, and Minimal Injury Hazard Level boundaries for the charge weight.

4.2 COMPARISON OF RANGE-TO-EFFECT CURVES

As shown in Figures 5 and 6, the Glazing Hazard Guide injury-based range-to-effect curves are more conservative than the injury-based curves. In fact, data from the multi-hit glass penetration tests described previously suggests that the injury-based curves are still conservative, although there were insufficient data points to quantify the conservatism.

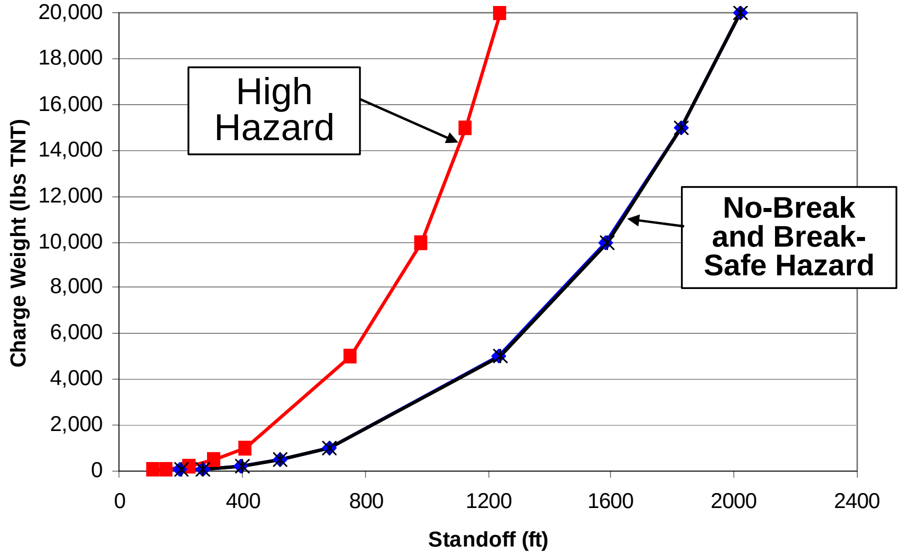

Figure 5. Glazing Hazard Guide Range-to-Effect Curves Generated Using HazL

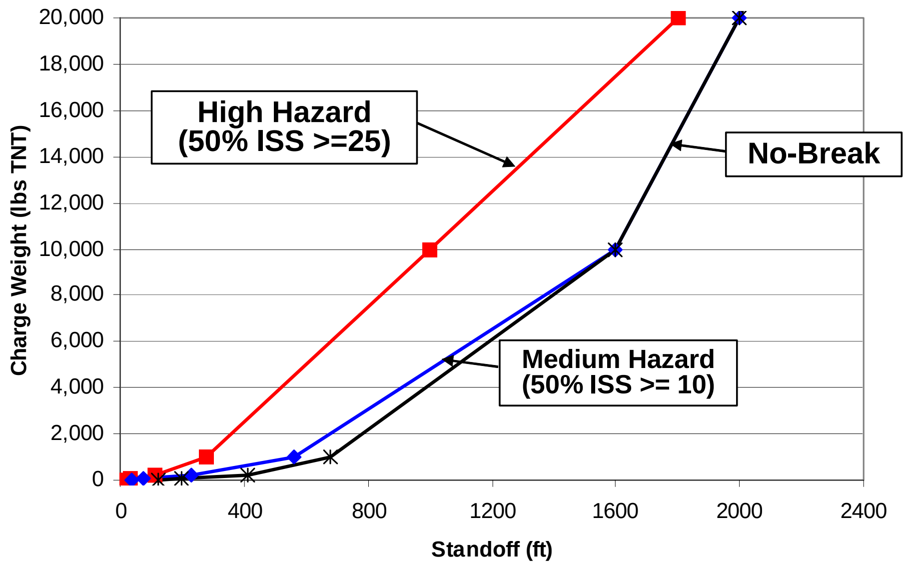

Figure 6. Injury-Based Range-to-Effect Curves Generated Using MHGP

5 Injury Based Glass Hazard Assessment PDA Tool

The injury based range-to-effect data has been implemented into a PDA tool, allowing a user in the field to quickly determine the expected injury risk based on window, threat, and human position parameters. An updated injury hazard assessment will be displayed as the user inputs or changes parameters.

To use the PDA Tool, the user first selects the glass type, window dimensions, and thickness(es) (Figure 6). Then they select the person's position relative to the window, which includes standoff (4.95 ft, 9.84 ft, or 16.40 ft, 1.5m, 3 m, or 5 m, respectively) and offset from the center of the window (either centered or offset by 15°). Finally the user will select the threat, composed of a charge weight and a standoff. Any charge weight between 20 and 500,000 pounds of TNT equivalent can be selected. For charge weights other than those previously calculated, the hazard level boundary will be extrapolated, and an injury hazard assessment will be returned.

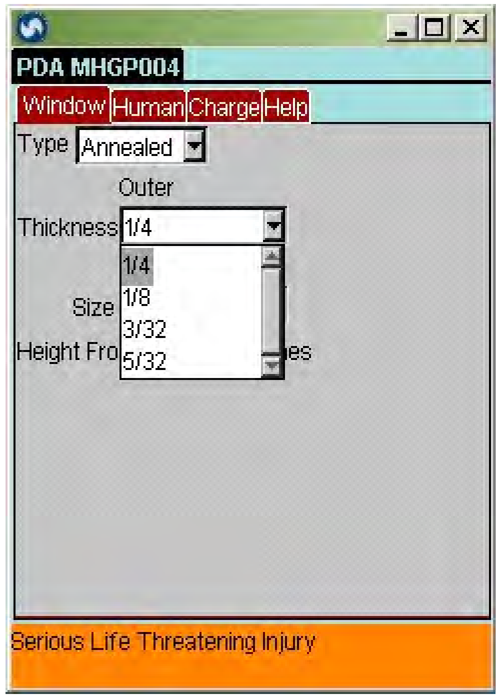

Figure 6. Glass Injury Hazard Assessment PDA Tool

6 Incorporation of MHGP model into HazL

The hazard level definitions in HazL were originally based only on the British Glazing Hazard Guide criteria. Because the data from the MHGP test program showed that the British Glazing Hazard Guide criteria were conservative, the decision was made to incorporate the MHGP code into HazL.

This updated version of HazL (version 1.2, Figure 7)) still includes the traditional hazard level definitions, but also includes an option to use the Multi-Hit Glass Penetration Model. Since the MHGP is based on statistical distributions, and each execution of the code may produce slightly different results, the user is given the opportunity to run the MHGP Model for any number of iterations. When the user selects the MHGP version of HazL, a new Human Positioning input window is presented. The Human Positioning window requests the inputs of the human standoff and offset from the center of the window parameters. Hazard level results are displayed on-screen and in program-generated text files. If multiple iterations are selected, the average results are displayed on-screen, while the individual executions results are stored in text files. Results displayed on-screen include the Injury Hazard Level (as defined in Table 1) and the ISS.

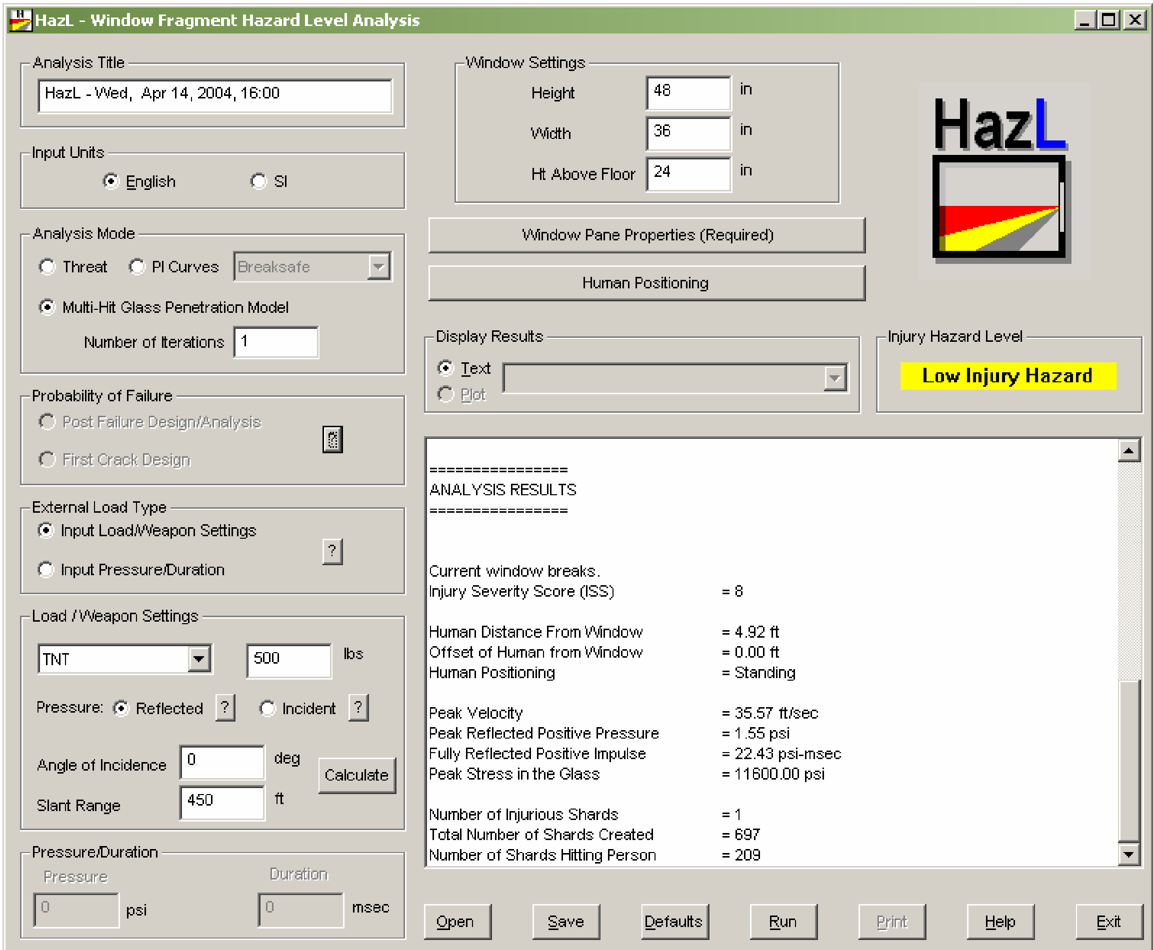

Figure 7. HazL version 1.2 Interface with MHGP Analysis Results

7 Conclusion

Traditional hazard criteria based on the British Glazing Hazard Guide have been shown are conservative. For design of new window glazing, it is still recommended that this approach be used. However, by conducting glass hazard level assessments with injury-based calculations, particularly for existing facilities, a more realistic assessment can be made which can prevent the costly and unnecessary window retrofits. With the incorporation of the MHGP into HazL and the development of the PDA Tool, injury based glass hazard assessments have become more accessible.

References

"Engineering Guidance for Windows and Doors Subjected to Blast Loads—ETL," Department of the Army, US Army Corps of Engineers, June 2003.

"Glazing Hazard Guide," presented in volumes entitled "Tables," "Charts," "Cubicle Stand-offs Tables and Charts," and "Control Points from Trials," Security Facilities Executive (SAFE), an Agency of the UK Cabinet Office, Office of Public Services, June 1997.

Meyer, Sarah B., Becvar, Keith E., Stevens, David J., 2004. "Injury Based Glass Hazard Assessment, Range-to-Effect Curves," Contract Number DACA45-02-D-0004, ARA Project Number 10626, Applied Research Associates, San Antonio, Texas, forthcoming.

Meyer, Sarah B., Becvar, Keith E., Stevens, David J., 2004. "Injury-Based Glass Hazard Assessment PDA Tool, User's Guide," Contract Number DACA45-02-D-0004, ARA Project Number 10626, Applied Research Associates, San Antonio, Texas, forthcoming.

Stevens, David J., 2002. "Test Report, Main Tests: Glass Debris Visualization, Analysis, and Prediction," TSWG Contract N39998-99-C-0671, ARA Project Number 0515, Applied Research Associates, San Antonio, Texas, April 8.

Stevens, David J., Meyer, Sarah B., Barsotti, Matthew A., Becvar, Keith E., and Marchand, Kirk A., 2002. "Final Technical Report, Glass Debris Visualization, Analysis, and Prediction," TSWG Contract N39998-99-C-0671, ARA Project Number 0515, Applied Research Associates, San Antonio, Texas, December 31.

Young, L.A., Becvar, K.E., Bass, C.D., 2002. "Extensions to ORCA-Glass to Provide Multi-Hit Capability," TSWG Contract N41756-01-C-7448, ARA Project Number 0675, Applied Research Associates, San Antonio, Texas, December.

Sarah Meyer *is a Staff Scientist at Applied Research Associates in their San Antonio, Texas office. She received a BS in Mathematics from McMurry University and studied graduate level Applied Mathematics at Texas Tech University. Mrs. Meyer has worked at ARA for the past two years in the areas of numerical and statistical modeling. Her recent experience includes developing the Shard Fly-Out Model.*

Lyn Little *is a Logistics Management Specialist for the US Army Technical Center for Explosives Safety (USATCES). Mr. Little received a BS in Industrial Technology from Illinois State University and has worked in the explosives safety field for the US Army for the past 16 years.*

Ed Conrath *is a structural engineer with the U.S. Army Corps of Engineers, Omaha District. He has been with the Corps since December 1974 and is currently assigned to the Protective Design Center. Mr. Conrath is actively involved in the development of standards and criteria for use of glazing in blast environments. He holds a BS in Civil Engineering from the University of Nebraska at Omaha, is a registered Professional Engineer in the state of Nebraska.*